$U(1)'$-extended Supersymmetric Standard Model

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Seminar at Carleton University (January 27, 2009)

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: $U(1)'$ as an alternative to R-parity

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- . . .

Outline

- Why Supersymmetry (SUSY)?
- Why SUSY companion symmetry?
- R-parity : popular
- TeV scale $U(1)'$ gauge symmetry : alternative
- Collider implications

Why Supersymmetry?

Higgs is special in the SM

Standard Model (SM) particle contents

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quark (Q), Lepton (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (G), $W^{\pm}$, Z

gauge group = $SU(3)_C \times SU(2)_L \times U(1)_Y$

(All known forces except for gravity)

Higgs: the only scalar (spin 0) particle and the only undiscovered particle.

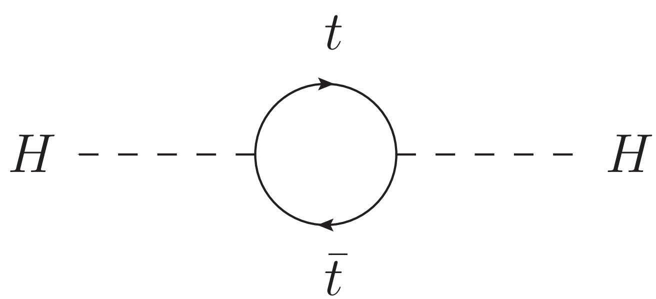
Higgs scalar can explain the masses of the fermions and gauge bosons.

(Otherwise, they should be massless.)

Discovery of the Higgs is one of the major goals in the LHC (Large Hadron Collider) experiments.

Higgs is a solution and a problem

Higgs (spin 0) mass is severely divergent with quantum correction.



$$\delta m_H^2(\text{top}) = -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \cdots \quad (\Lambda = \text{cutoff scale of theory})$$

Quadratic divergence (Λ^2) in the scalar mass^2 correction.

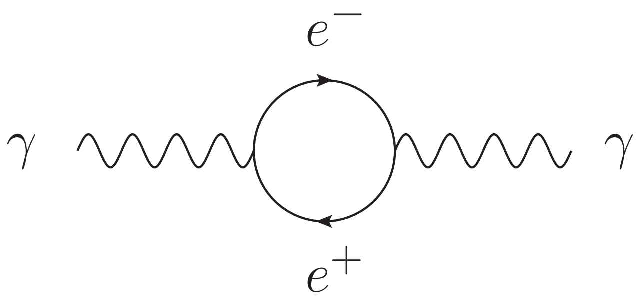
If SM is valid up to gravity scale ($\Lambda = M_{\rm Pl} = 10^{19}$ GeV), natural Higgs mass is close to $\mathcal{O}(10^{19}\ \text{GeV})$.

Physical Higgs mass should be $\mathcal{O}(100\ \text{GeV})$.

Something is missing in the SM $\longrightarrow$ great motivation for new physics.

What about other particle masses?

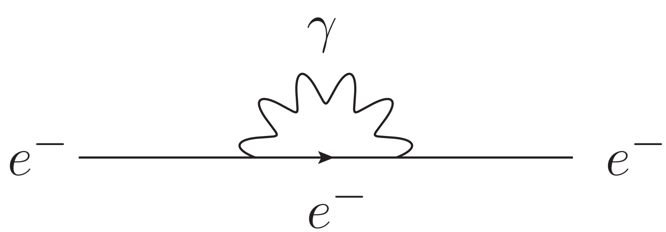
(i) Spin 1 particle (photon):



$$\delta m_\gamma = 0$$

"Spin 1 particle (gauge boson) mass is protected by the gauge symmetry."

(ii) Spin 1/2 particle (electron):



$$\delta m_e \simeq 2\frac{\alpha_{\rm em}}{\pi} m_e \log\frac{\Lambda}{m_e} \simeq 0.24 m_e$$

$$\left(\text{for } \Lambda = M_{\rm Pl} = 10^{19}\ \text{GeV}\right)$$

"Spin 1/2 particle (fermion) mass is protected by the chiral symmetry."

Look for a new symmetry to protect spin 0 particle (scalar) mass.

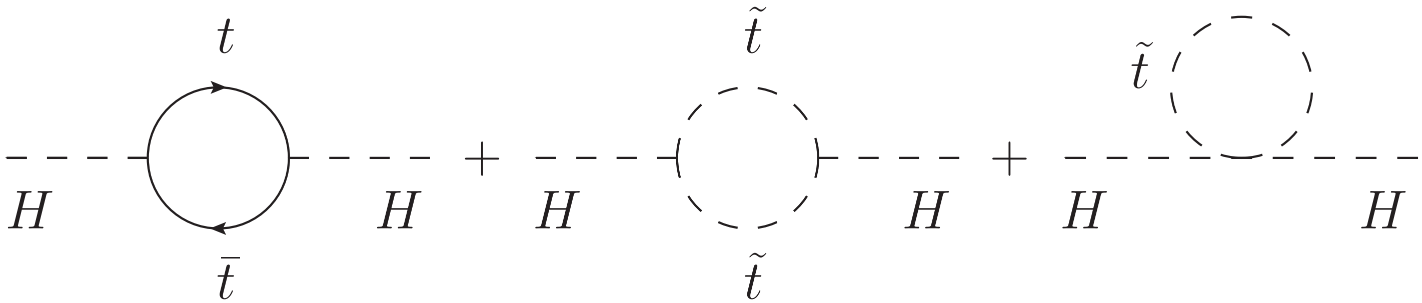
Supersymmetry (SUSY)

SUSY : fermion (spin 1/2) $\leftrightarrow$ boson (spin 0, 1)

SUSY predicts (superpartners) of different spins, which doubles the particle contents.

Spin 0	Higgs (H)	Spin 1/2	Higgsino ($\widetilde{H}$)
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark ($\widetilde{Q}$), Slepton ($\widetilde{L}$)
Spin 1	γ, G, $W^{\pm}$, Z	Spin 1/2	$\widetilde{\gamma}$, $\widetilde{G}$, $\widetilde{W}^{\pm}$, $\widetilde{Z}$

Higgs problem motivates SUSY



$$
\begin{aligned}
\delta m_H^2(\mathrm{top}+\mathrm{stop}) &= \left(-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2+\cdots\right)+\left(\frac{3}{8\pi^2}\lambda_t^2\Lambda^2+\cdots\right) \\
&= -\frac{9}{8\pi^2}\lambda_t^2 m_{\tilde{t}} \log\frac{\Lambda}{m_{\tilde{t}}}+\cdots
\end{aligned}
$$

Quadratic divergence (Λ^2) cancelled by the supersymmetry!

"Spin 0 particle (scalar) mass can be protected by the supersymmetry."

SUSY in literature

Although there are other ideas ...

SPIRES database search results	
"`Supersymmetry`" in title	7200 papers
"`Higgs`" in title	8500 papers

Discovery of SUSY signal is another major goal in the LHC experiments.

Which supersymmetric SM?

- Certain: Supersymmetry is a prevailing new physics scenario.
- Not certain: What is the correct Supersymmetric SM?

Supersymmetry needs a “SUSY companion symmetry”.

Supersymmetric SMs can be distinguished by this additional symmetry.

Different Supersymmetric SMs may provide different predictions.

(ex) Best search schemes for Higgs and SUSY may depend on model.

$\longrightarrow$ It is important to develop viable SUSY models (or viable SUSY companion symmetries) and their implications.

Why SUSY companion symmetry?

General SUSY

$$
\begin{aligned}
W &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c \\
&+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

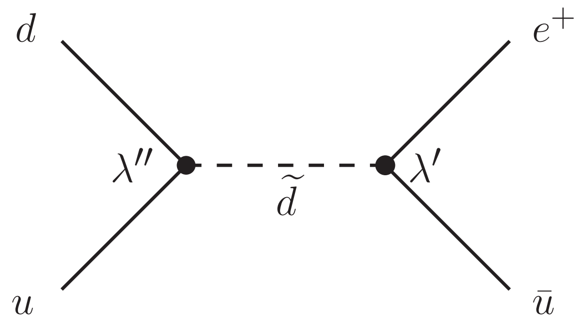
Lepton number ($\not{\mathcal{L}}$) and/or baryon number ($\not{\mathcal{B}}$) violating terms

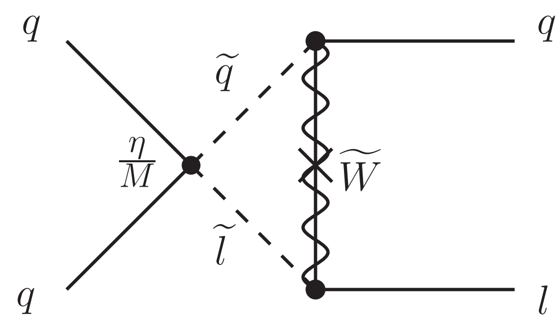
at renormalizable and non-renormalizable levels:

(1) **one of the most general predictions of SUSY.**

(2) also source of some problems.

1. Proton decay





[Dim 4 $\mathcal{L}$ violation $\&$ Dim 4 $\mathcal{B}$ violation]

$\lambda LLE^c + \lambda' LQD^c \;\&\; \lambda'' U^c D^c D^c$

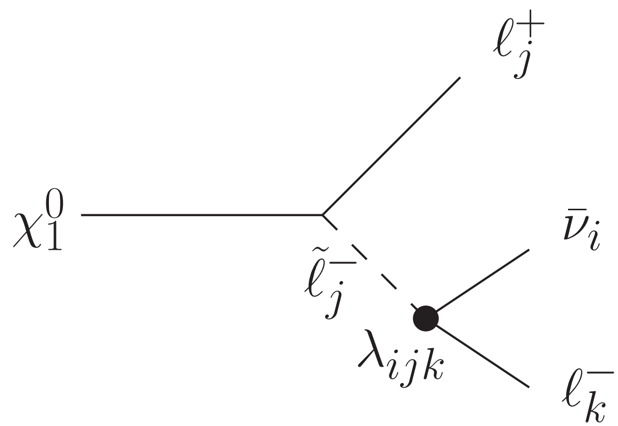
[Dim 5 $\mathcal{B}\&\mathcal{L}$ violation]

$\frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c$

To satisfy τ_p (proton lifetime) $\gtrsim 10^{29}$ years,

- Dim 4: $|\lambda_{LV} \cdot \lambda_{BV}| \lesssim 10^{-27}$ (if one is 0, the other can be sizable)
- Dim 5: $|\eta| \lesssim 10^{-7}$ $($for $\Lambda = M_{\rm Pl})$

2. Neutralino (Cold Dark Matter candidate) decay

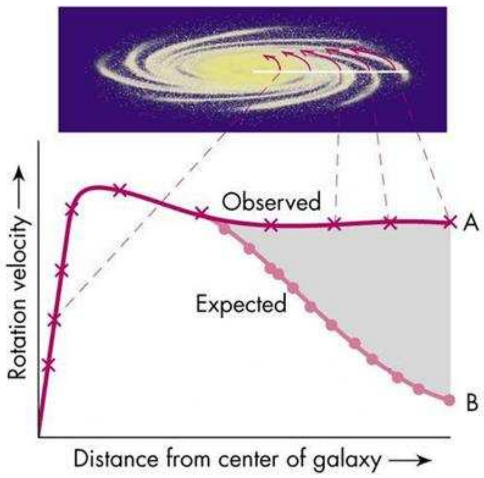


$$\Gamma = \lambda_{ijk}^2 \frac{\alpha}{128\pi^2} \frac{m_{\chi_1^0}^5}{m_{\tilde{f}}^4}$$ (for $\chi_1^0 \sim$ photino)

To be a viable dark matter, $\tau_{\chi_1^0} \gtrsim 14 \times 10^9$ years (Universe age).

$$|\lambda|, |\lambda'|, |\lambda''| \lesssim 10^{-20}$$

Cold Dark Matter



$$\frac{mv^2}{r} = G\frac{Mm}{r^2}$$

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

We need dark (electrically neutral) matter to explain galaxy rotation curves and other evidences (gravitational lensing, CMB anisotropy, etc).

Dark matter should be cold (non-relativistic) to form the galaxies and their clusters.

Dark matter is another important reason the SM should be extended.

Cold Dark Matter (CDM) candidate

A viable dark matter candidate should

- be Cold (non-relativistic), Neutral, Stable.
- explain relic density (WMAP+SDSS) : 22% of total energy density
- satisfy direct detection experiments limit (CDMS, XENON, $\cdots$)

SM: neutrino ($m_\nu \lesssim 0.1 \text{ eV}$) is neutral and stable, but not cold.

SUSY: neutralino ($\widetilde{\gamma}$, $\widetilde{Z}$, $\widetilde{H}$) is neutral and heavy (therefore, cold)

$\longrightarrow$ CDM candidate if stable.

SUSY needs a companion mechanism or symmetry.

(for stability of proton and dark matter)

R-parity

: Most popular SUSY companion symmetry

R-parity

$$R_p[\mathrm{SM}] = \mathrm{even}, \quad R_p[\mathrm{superpartner}] = \mathrm{odd}$$

$\longrightarrow$ Lightest superpartner (LSP) is absolutely stable.

(i) LSP dark matter: Provides a CDM candidate if a neutralino is the LSP.

SUSY with R-parity

$$
\begin{aligned}
W_{R_p} &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \cdots \\
&+ \frac{\eta_1}{\Lambda} QQQL + \frac{\eta_2}{\Lambda} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

(ii) over-constraining of R-parity: All renormalizable $\mathcal{L}$ violating and $\mathcal{B}$ violating terms are (unnecessarily) forbidden.

(iii) under-constraining of R-parity: Dimension 5 $\mathcal{L}\&\mathcal{B}$ violating terms still mediate too fast proton decay. (Weinberg [1982])

Look for an alternative

R-parity may be still valid, but possibilities are limited.

(ex) What if R-parity violating signals are found?

Try to find an alternative SUSY companion symmetry (without R-parity), which can

(i) allow $\mathcal{B}$ or $\mathcal{L}$ violating terms over-constrained by R-parity,

(ii) address proton stability (including non-renormalizable operators),

(iii) address dark matter issue (non-LSP dark matter).

TeV scale $U(1)'$ gauge symmetry
: Alternative to R-parity

Proton stability without R-parity :
HSL, Matchev, Wang [PRD (2008)]
HSL, Luhn, Matchev [JHEP (2008)]

CDM stability without R-parity :
Hur, HSL, Nasri [PRD (2008)]

Simultaneous Proton & CDM stability without R-parity :
HSL [PLB (2008)]
Hur, HSL, Luhn [JHEP (2009)]

Our model

$$U(1)' \;\rightarrow\; Z_6 = B_3 \times U_2$$

B_3 (Baryon triality) : stabilizes proton

U_2 (U-parity) : stabilizes hidden sector dark matter candidate

B_3 (Baryon triality) (Ibanez,Ross [1992])

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_3	0	-1	1	-1	-1	0	1	-1	$-\mathcal{B}+y/3$

B_3 has a selection rule of

$$\Delta\mathcal{B} = 3 \times \text{integer}$$

Lepton number ($\mathcal{L}$) is freely violated.

Baryon number ($\mathcal{B}$) can be violated only by $3 \times \text{integer}$.

Proton decay ($\Delta\mathcal{B} = 1$) : Forbidden.

Neutron-antineutron oscillation ($\Delta\mathcal{B} = 2$) : Forbidden.

U_2 (U-parity)

Consider hidden sector fields (SM singlets), which still interact with $U(1)'$.

$$W_{\text{hidden}} = \frac{\xi}{2} S X X$$

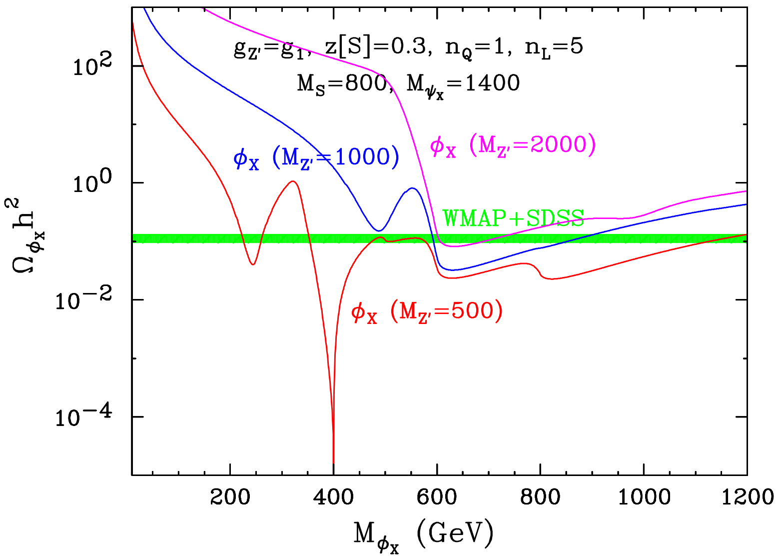
X : neutral and massive $\longrightarrow$ CDM candidate if stable.

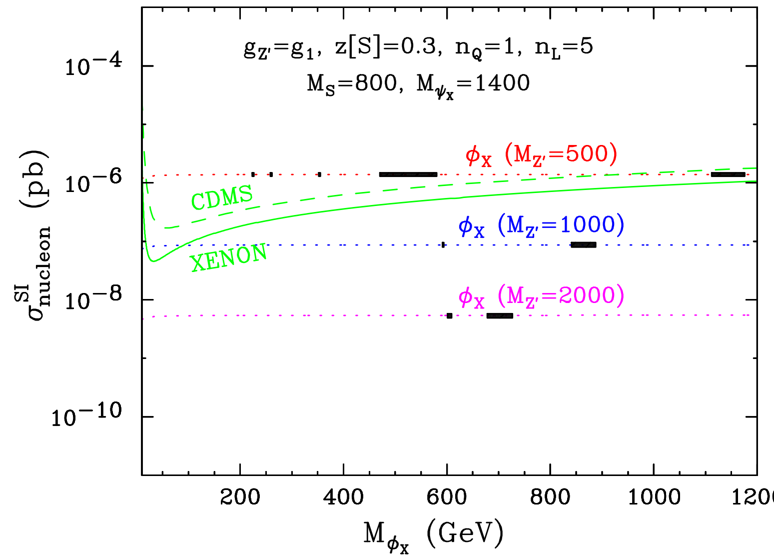
Introduce "U-parity"

U_p[MSSM] = even, U_p[hidden] = odd

Lightest U-parity particle (LUP) is stable due to U-parity.

What about relic density and direct detection constraints?





[Relic density] [Direct detection cross section]

$\longrightarrow$ LUP is a viable dark matter candidate.

A unified picture of the stabilities in the observable and hidden sectors

$$U(1)' \to Z_{N_1}^{obs} \times Z_{N_2}^{hid}$$

MSSM sector

$Z_{N_1}^{obs}$ (B_3)

: stable proton

Hidden sector

$Z_{N_2}^{hid}$ (U_2)

: stable dark matter

A single $U(1)'$ gauge symmetry provides stabilities for proton (MSSM sector) and dark matter (hidden sector).

$U(1)'$ solution to the μ-problem

$$W = \mu H_u H_d \quad (\mu : \text{mass parameter})$$

μ-problem: $\mu \sim \mathcal{O}$(EW) to avoid fine-tuning in the EWSB.

Why is $\mu \neq \mathcal{O}(\Lambda)$? (Kim, Nilles [1984])

$U(1)'$ can solve the μ-problem.

$$W = hSH_u H_d \quad (\text{no mass parameter})$$

$$\mu_{\text{eff}} = h \langle S \rangle \sim \mathcal{O}(\mathrm{EW/TeV})$$

S is a Higgs singlet that breaks the $U(1)'$ spontaneously.

How to get $U(1)' \to B_3 \times U_2$

In the minimal fields assumption of

$$N_{\text{Higgs pair}} = 1, \quad N_{\text{fermion family}} = 3, \quad N_{SU(2)_L \text{ exotics}} = 0$$

1. Solve the μ-problem with $U(1)'$ gauge symmetry (SH_uH_d).
2. Require $\mathcal{L}$ violating terms such as λLLE^c .
3. Require SXX term (TeV scale mass for hidden sector particle X).

Then $B_3 \times U_2$ is **automatically invoked**, and the proton and LUP are stable.

Recap: SUSY with R-parity vs. SUSY with $U(1)'$

	R_p	$U(1)' \rightarrow B_3 \times U_p$
proton	unstable w/ dim 5 op. (R_p)	**stable (B_3)**
dark matter	stable LSP (R_p)	**stable LUP (U_p)**
RPV signals	impossible	**possible ($\mathcal{L}$ violation)**

TeV scale $U(1)'$ is an attractive alternative to R-parity

with distinctive features.

LHC implication (I)

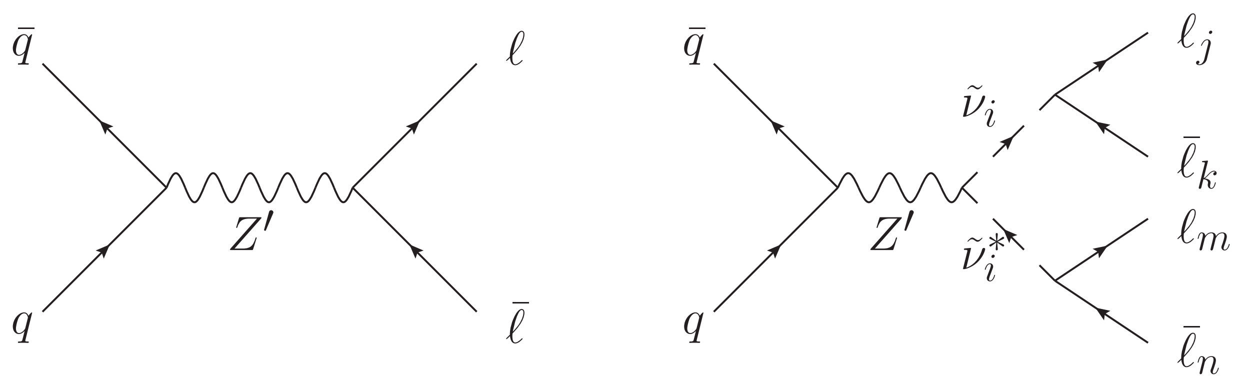
: SUSY signal search via Z' resonance

HSL [arXiv:0812.1854]

Connection of $U(1)'$ and R-parity violation at LHC

- TeV scale $U(1)'$: Z' resonance in dilepton channel
  (ex: $pp \longrightarrow Z' \longrightarrow e^+e^-$)

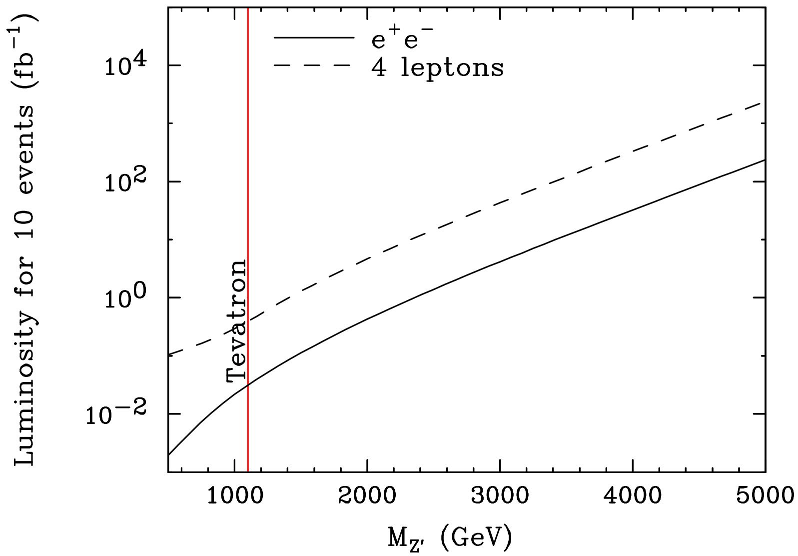
- $\mathcal{L}$ violation: Z' produces LSP pair, and the LSP decays into SM particles through $\mathcal{L}$ violating interaction
  (ex: $pp \longrightarrow Z' \longrightarrow \widetilde{\nu}\widetilde{\nu}^* \longrightarrow 4$ leptons)



Discovery reach at the LHC (luminosity for 10 events)

$pp \to Z' \to e^+e^-$ (Z' discovery) for single lepton flavor

$pp \to Z' \to \widetilde{\nu}\widetilde{\nu}^* \to 4\ell$ (SUSY signal discovery) for single $\widetilde{\nu}$ flavor



- $p_T > 20$ GeV, $|\eta| < 2.4$ (each lepton)
- $|m_{\rm inv} - M_{Z'}| < 3\Gamma_{Z'}$ ($m_{\rm inv} = m_{e^+e^-}, m_{4\ell}$)

Results of numerical analysis

For $M_{Z'} = 2\,\mathrm{TeV}$, the required luminosity for discovery:

- 2 leptons (10 events): $L = 0.43\,\mathrm{fb}^{-1}$
- 4 leptons (10 events): $L = 4.7/\mathrm{Br}(4\ell)\,\mathrm{fb}^{-1}$ ($0 \leq \mathrm{Br}(4\ell) \leq 1$)

(Discoveries in the early stage of the LHC possible!)

LSP pair	$eeee$	$eee\mu$	$ee\mu\mu$	$e\mu\mu\mu$	$\mu\mu\mu\mu$	Br(4ℓ)
$\widetilde{\nu}_e \widetilde{\nu}_e^*$	0	0	1	2	1	4/36
$\widetilde{\nu}_\mu \widetilde{\nu}_\mu^*$	1	2	1	0	0	4/36
$\widetilde{\nu}_\tau \widetilde{\nu}_\tau^*$	1	4	6	4	1	16/36

(Light lepton production ratio for $|\lambda_{ijk}|$ = constant $\gg$ $|\lambda'_{ijk}|$)

$$(\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c)$$

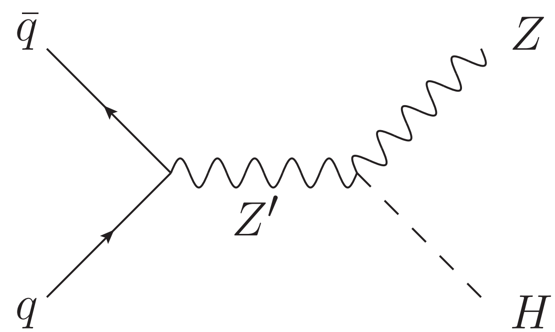
LHC implication (II)

: Higgs search via Z' resonance

[in preparation]

Sizable Z'-H-Z coupling

$Z' \longrightarrow HZ$: First mentioned by Gunion, Haber, Roszkowski in 1987, but it has been almost a deserted channel.

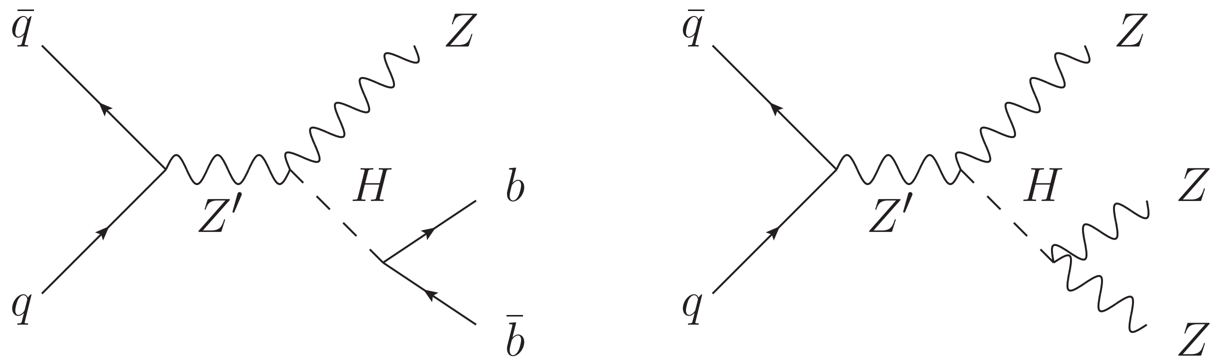


$$\begin{aligned}\mathcal{L}_{KE} &= |D_\mu H|^2 = |(\partial_\mu + i g_{Z'} z[H] Z'_\mu + \cdots)H|^2 \\ &= 2 g_{Z'} z[H] Z'_\mu (h_R \partial^\mu h_I - h_I \partial^\mu h_R) + \cdots\end{aligned}$$

with $H = h_R + i h_I$.

h_I: longitudinal mode of Z (Higgs mechanism).

Z'-H-Z vertex with gauge coupling $g_{Z'} z[H]$.



This can be utilized for many purpose:

1. For $m_H \ll 2M_Z$: Higgs discovery through on-shell Z' resonance.
2. For $m_H \gtrsim 2M_Z$: Higgs discovery through purely leptonic resonance
3. Signals will rule out $U(1)_{B-L}$ since $z_{B-L}[H] = 0$.
4. Works even for leptophobic (no lepton coupling) Z'.

(Need numerical analysis to compare existing Higgs search schemes.)

Recap: Purely leptonic resonances at the LHC

- 2ℓ resonance at $m_{2\ell} \sim M_{Z'}$: Z' discovery
- 4ℓ resonance at $m_{4\ell} \sim M_{Z'}$: SUSY discovery (for $\widetilde{\nu}$ LSP)
- 6ℓ resonance at $m_{6\ell} \sim M_{Z'}$: Higgs discovery (for $m_H > 2M_Z$)

All invariant masses are commonly $m_{\rm inv} \sim M_{Z'}$

: Z' tells us where to look.

Allowing jets and MET can test more variety of scenarios

: (ex) Higgs with $m_H < 2M_Z$ (2ℓ + $2b$-jet), other type LSP, etc.

Z' is a great venue to discover other important new physics.

(possibly in the early stage of the LHC experiments!)

Summary

1. Major discovery goals of LHC experiments:

   (1) Higgs (missing component of the SM)

   (2) SUSY (arguably, best-motivated new physics from Higgs)

2. SUSY needs a companion symmetry:

   - R-parity can address stability of the proton and dark matter (LSP) simultaneously.

   - TeV scale $U(1)'$ can also address stability of the proton and dark matter (LUP) simultaneously.

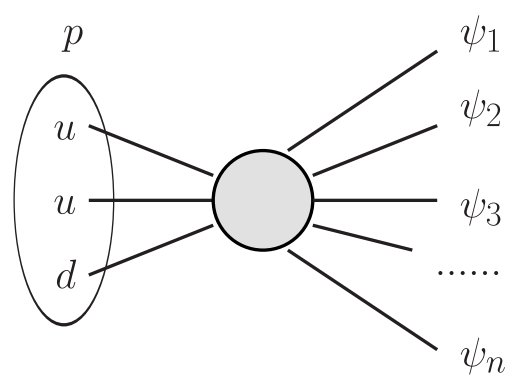
3. Replacing R-parity with TeV scale $U(1)'$ $\longrightarrow$ a viable & well-motivated alternative SUSY model with distinguishable predictions (Z', new SUSY signals, new Higgs signals, etc).

Backup Slides

Discrete symmetries in presence of exotics

- The discrete symmetries may be changed with additional particles.
- The MSSM discrete symmetries still hold among the MSSM fields.

For a physics process which has only MSSM fields in its effective operators (such as proton decay), we can still discuss with Z_N^{MSSM}.



$$\text{operator[p-decay]} = \left(\frac{1}{M}\right)^m [\underbrace{F_1 F_2 F_3 F_4 F_5 \cdots}_{\text{MSSM fields only}}]$$

Our another model

$$U(1)' \rightarrow Z_6 = L_3 \times U_2$$

L_3 : prevent proton decay (with help of $U(1)'$)

U_2 : prevent CDM decay

L_3 selection rule: $\Delta\mathcal{L} = 3 \times \text{integer}$

Baryon number ($\mathcal{B}$) is freely violated.

Lepton number ($\mathcal{L}$) can be violated by only $3 \times \text{integer}$.

Neutrinoless double β decay ($\Delta\mathcal{L} = 2$) : Forbidden.

Proton may still decay if decay products has 3, 6, $\cdots$ leptons.

L_3 + some help from $U(1)'$ can protect proton up to dimension 5 level.

Residual discrete symmetry of $U(1)'$

Z_N emerges from $U(1)'$ naturally (after integer normalization):

$$N = z[S]$$

$$q[F_i] = z[F_i] \bmod N$$

($z[F_i]$: $U(1)'$ charge, $q[F_i]$: Z_N charge) for each field F_i.

S is the Higgs singlet that breaks the $U(1)'$ spontaneously.

Neutrino mass

Observed neutrino mass ($m_\nu \lesssim 0.1$ eV) needs an explanation.

1. Majorana neutrino: with see-saw mechanism (Minkowski [1977])

$$W = y_N H_u L N^c + m N^c N^c$$

2. Dirac neutrino: natural suppression possible in $U(1)'$ model (Langacker [1998])

$$W = y_N \left(\frac{S}{\Lambda}\right) H_u L N^c$$

3. No RH neutrino (N^c): $\mathcal{L}$ violation (Hall, Suzuki [1984]) (Grossman, Haber [1998])

$$W = \mu' H_u L + \lambda L L E^c + \lambda' L Q D^c$$